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ORIGIN OF THE EARTH'S OCEAN BASINS

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ABSTRACT

The Earth's original ocean basins were mare-type basins produced 4 billion years ago by the flux of asteroid-sized objects responsible for the lunar mare basins. Scaling upwards from the observed number of lunar basins for the greater capture cross-section and impact velocity of the Earth indicates that at least 50% of an original global crust would have been converted to basin topography. These basins were flooded by basaltic liquids in times short compared to the isostatic adjustment time for the basin. The modern crustal dichotomy (60% oceanic, 40% continental crust) was established early in the history of the Earth, making possible the later onset of plate tectonic processes. These later processes have subsequently reworked, in several cycles, principally the oceanic parts of the Earth's crust, changing the configuration of the continents in the process. Ocean basins (and oceans themselves) may be rare occurrences on planets in other star systems.

INTRODUCTION

It has recently been pointed out by Lowman (1976) that the combination of extraterrestrial and terrestrial data yields a common evolutionary pattern for all the terrestrial planets. An important implication of this model is the nature of the Earth's original crust: it is inferred to have been global in extent and intermediate (roughly andesitic) in compostion. The present continents are then considered the greatly altered, "redifferentiated" (Lowman's term) remnants of this original global crust. The bulk composition of the modern continents is not far removed from the suggested original material, and terrestrial evidence alone supports the reworked nature of the continental crust. But the inference of global extent rests almost entirely on interplanetary analogy, and runs counter to most modern views (as pointed out by Lowman, 1976; 1973), which favor continental growth over geologic time.

_If_ the Earth did begin with a global crust, then more than 50% of that crust must have been "destroyed" over geologic time in order to reach the present 60/40 oceanic/continental crustal division. The modern ocean basins are very young, and are generally agreed to be a consequence of plate tectonic processes. The creation of new (oceanic) crust at spreading centers requires compensating destruction of crust elsewhere. This destruction occurs principally at subduction zones, where one plate overrides another. McKenzie (1969) has shown that _continental_ crust more than 5 km thick is too buoyant to be subducted; the required destruction must be taken up by subduction of _oceanic_ crust. Continental crust remains more or less intact as new oceanic crust is formed at the expense of older oceanic

crust. Plate tectonics cannot convert an original global continental crust into the observed modern dichotomy.

Furthermore these same plate tectonic processes cannot occur unless the crustal dichotomy is already established, because subductable crust is required for subduction to compensate for newly formed oceanic crust. Burke et al.(1976) suggest that modern plate tectonics goes back at least 2 billion years, and that prior to this kind of "microplate" tectonic environment existed. Engel et al.(1974) infer from a variety of geochemical parameters that a major change in tectonic style occurred on the Earth 2.5 billion years ago, perhaps marking the onset of modern(large plate) plate tectonics. Wise(1974) argues for the modern ratio of oceans/continents having persisted throughout most of geologic time. It would appear that, from the above, the crustal dichotomy of the Earth was established early in its history.

The modern dichotomy (of high density/low density crust) of the Earth superficially resembles the maria/highlands dichotomy of the Moon, Mercury and Mars. The ratio of new/old crust (oceanic/continental or maria/highlands) increases with the size of the planet, being roughly 30/70 for the Moon, 40/60 for Mars and 60/40 for the Earth. The lunar dichotomy is largely due to a period of intense bombardment by basin-forming objects some 4 billion years ago (Tera et al., 1974). The impacting bodies created large, shallow basins,

such as the Orientale basin (Head, 1974), which, on the lunar frontside, were subsequently flooded by basaltic lavas. Even the large, shallow, irregular maria (of which Oceanus Procellarum is the most extensive) may have been the sites of large impacts (Wood and Head, 1976; Wood, 1976. private communication). Murray et al. (1975) and Chapman (1976) argue that these basin-forming impacts were common to all the terrestrial planets, and Wetherill (1975, 1976) has shown that dynamically plausible orbits exist for such an event.

Because it is impossible that the Earth could escape such a bombardment common to the entire inner solar system, this paper investigates whether or not such a bombardment could account for the modern crustal dichotomy of an Earth which originally had a global crust.

TERRESTRIAL IMPACT PARAMETERS

A lower limit to the number of basin-forming impacts that must have occurred on the Earth 4 billion years ago can be obtained by scaling upwards from the observed number of lunar basins to the greater capture cross-section and impact velocity of the Earth. Because the Earth and Moon at that time were in roughly their present configuration, both bodies should have experienced the same spatial distribution of incoming objects. It is therefore reasonable to treat this as a scaling problem.

Consider a group of objects deflected into Apollo-type orbits. These asteroids represent the closest modern example of the basin-forming objects that impacted the Moon 4 billion years ago (Wetherill, 1975). Such objects will approach the Earth-Moon system with a relative velocity between 15 and

20 km/sec (Öpik, 1966). Figure 1a shows the impact velocity at the surfaces of the Earth and Moon, and the ratio of these impact velocities, as a function of approach velocity. The 15-20 km/sec range of approach velocities is shown by the bar. The impact velocity at the Earth varies from 18.7 to 22.9 km/sec; for the Moon, the corresponding range is 15.2 to 20.1 km/sec. The ratio of impact velocities is 1.23 to 1.14. Equivalent objects strike the Earth some 15-20% faster than they do the Moon.

It is possible to convert impact velocity to crater diameter D through the energy scaling relation, which can be written (Hartmann, 1965)

$$D = CE^k = C\left[\frac{1}{2}MV^2\right]^k$$

where C and k are constants and the energy E is assumed due to the kinetic energy of an object with mass M and impact velocity V. The constant C is not well determined. We use the ratio of crater diameters on the Earth to those on the Moon:

$$\frac{D_\oplus}{D_☾} = \left[\frac{(MV^2)_\oplus}{(MV^2)_☾}\right]^k$$

which eliminates the constant C. If objects of equal mass are considered, then the relation becomes

$$D_\oplus = D_☾\left[\frac{V_\oplus}{V_☾}\right]^{2k}$$

where $V_\oplus$ and $V_☾$ are the impact velocities at the surfaces of the Earth and Moon as discussed above.

This relation now depends on k. As discussed by Hartmann (1965), values of k between 1/3.0 and 1/3.4 have been suggested in the literature. Figure 1b is a plot of $D_{\oplus}/D_{☾}$ as a function of approach velocity for two different values of k. In the velocity range of interest, the resulting diameter ratio is not very sensitive to k, varying only from 1.15 to 1.13 (for k = 1/3.0 to k = 1/3.3 respectively) for the worst case of 15 km/sec approach. Craters on the Earth will be 11-15% larger than those formed on the Moon by identical objects, as shown in Figure 1b.

The Earth also collects more of these objects. The lower limit on this is the ratio of the physical cross-sections of the Earth and Moon. This goes as the square of the ratio of their physical radii: $(R_{\oplus}/R_{☾})^2 = 3.67^2 = 13.47$. Were there no other considerations, the Earth would gather thirteen and a half times as many objects, but have the same number of craters <u>per unit area</u> as the Moon. But the Earth has a significantly larger <u>gravitational</u> radius than the Moon, and therefore a larger gravitational cross-section. Figure 1c shows the gravitational radius of the Earth and that of the Moon as a function of approach velocity, using a relation given by Wetherill (1974):

$$R_g = R\sqrt{1 + \frac{V_{esc}^2}{V^2}}$$

where R_g and R are the gravitational and physical radius of the planet, V_{esc} is the escape velocity and V is the approach velocity. Also shown in this figure is the ratio of the gravitational radius of the Earth to that for the Moon. Over the range of approach velocities of interest,

$R_g^{\oplus}/R_g^{☽}$ varies from 4.52 to 4.18, decreasing with increasing velocity. The Earth's gravitational cross-sectional area is 17.4 to 20.4 times larger than the Moon's, compared to the physical cross-section ratio of 13.7. The Earth therefore collects some 17-20 times as many objects of a given mass as does the Moon (or 1.3-1.5 times as many per unit area). If even 30% of the lunar surface was covered by basins (see below), the at least 45% of the Earth's surface was disrupted by a similiar event 4 billion years ago. A more careful estimate is made below.

THE SIZE DISTRIBUTION OF LUNAR BASINS

The actual number and diameters of lunar basins are not precisely known. Table I is compiled from the published lists of Hartmann and Wood (1971), Stuart-Alexander and Howard (1970) and Howard et al. (1974). The adopted diameter (column 6) is generally the "most prominent" ring of Hartmann and Wood, where available. Capital letters in column 1 designate basins not listed by Hartmann and Wood; for some of these, diameters were estimated from the Figure 14 in Howard et al. Craters larger than 200 km or showing evidence of mare fill are also included in Table I. The irregular mare of Oceanus Procellarum is represented by two "artificial basins" (900 and 450 km across), as is the irregular mare at 30°W, +8° ("Euclides"). "Mare Gargantua", which appears in a recent compilation by Wood and Head (1976), is not included here; its large diameter (> 2500 km) would significantly increase the total area of the Moon covered by basins. Another very large basin ("Super Basin") suggested by Howard et al. (1974), also appears on the list of Wood and Head, and is included here.

Figure 2a is a histogram of the basins and craters from our list. The large craters in the 100-199 km diameter range are under-represented due to observational selection. This may apply to the adjacent bin as well. Therefore, large <u>craters</u> with diameter less than 300 km were not included in the <u>minimum</u> area count (see below). In Figure 2b, we plot a log cumulative number-log diameter curve for these basins, together with the solid line for highland craters from Hartmann (1966). Despite the small numbers, there appears to be a break at D = 500 km, which is also evident in the histogram (Figure 2a). At smaller diameters, the basins grade into the highland crater curve. This suggests the lunar surface may be saturated for craters larger than 500 km; smaller basins and craters may be depopulated by the obliterating effects of one large basin. Alternate interpretations are also possible; for example, two different populations of objects may be represented here. At the present, there is no way to determine the reality or significance of the 500 km break.

In determining the <u>minimum</u> total area of the Moon covered by basins, it is necessary to eliminate overlap between basins. Where small basins lie <u>inside</u> larger areas (see "Remarks" column in Table I), the small basins were discarded entirely (for example, basins 14, 17, 18, 19, 22, 23, 24 and 26 were not counted for this reason). When two basins overlap (for example, "Fauth" = Basin B overlaps Imbrium = Basin 1), the effective diameter of the smaller basin was decreased so as to count only the non-overlapping <u>area</u> of each basin. Mare Australe, whose rim is difficult to identify and whose diameter is therefore uncertain, was also eliminated in the minimum basin area count.

The total area of the Moon covered by large, non-overlapping basins is 32% of the available surface area. The total area of <u>all</u> basins and large craters in Table I is equivalent to 40% of the lunar surface area.

BASIN DISRUPTION OF THE EARTH'S SURFACE

The Earth should have collected 1.3-1.5 times as many objects per unit area as did the Moon. Each basin on the Earth was 11-15% larger than the corresponding crater on the Moon (for objects of the same mass). This means each terrestrial basin had roughly 28% more <u>area</u> than would the lunar basin produced by an equivalent object. Figure 3 shows the total equivalent area of the Earth's surface covered by basins as a function of approach velocity for all basins and for non-overlapping large basins only. For 32% of the lunar surface covered by basins, the corresponding figure for the Earth is 48-62% of the surface area. If we adopt the equivalent 40% coverage of the Moon, 60-78% of the Earth's surface could have been affected by basin formation.

The above scaling merely indicates the area of basins on the Earth, and does not represent the true fraction of the Earth's surface covered by basins (except in the unlikely case of no overlap between basins). How this basin area is distributed over the Earth depends on the probability of each new basin impacting fresh surface. This of course depends on the fractional area of the planet already covered by basins. Let A be the fractional area of the Earth covered by basins, and let $a_\oplus$ be the total basin area due to objects impacting the Earth. This quantity can be determined by scaling from the Moon's total basin area, which amounts to an equivalent of 40% of its surface area. Thus, for a median velocity of approach of 17.5 km/sec,

$$a_\oplus = a_{☾} \times 1.4 \times 1.28 = 0.72$$

That is, the basins forming on the Earth have an area equivalent to 72% of the Earth's surface area. This will be distributed over a fractional area

$$A = 1 - e^{-a_{\oplus}} = 0.51$$

or, over about 51% of the Earth's surface. This value obviously depends on the approach velocity, and ranges from 45% at high velocities to 55% at 15 km/sec. It would appear from the above that about 50% of the Earth's surface was covered by basins whose total area was equal to 72% of the Earth's surface area.

Not included above is the possibility of much larger basins than those observed on the Moon. D^{-2} scaling of basin numbers would suggest that, if there are 3 basins on the Moon with $D \geq 1000$ km (implying 56 such on the Earth), then on the Earth there could have been 6 basins with diameters in excess of 3000 km, and one of these would have been larger than 6000 km. While there is no guarantee that such large impacts did occur, if they did they would significantly add to the percentage of the Earth's crust affected by this period of basin formation.

Therefore, 4 billion years ago at least 50% of the surface of the Earth was disrupted by basin-forming impacts. This figure represents the minimum percentage of a global crust affected. No attempt has been made to account for the possibility of saturation of lunar basins (which may have occurred); the above figure is based on an absolute minimum number of basins observed on the Moon. The actual number of basin-forming objects impacting the Moon

was certainly higher than the number of surviving basins. For example, if "Super Basin" had occurred last on the Moon it would have destroyed at least eight basins with diameters between 280 and 435 km. There is no way to correctly estimate the number of smaller basins eradicated by the formation of an Imbrium or Orientale.

Another potential problem we have not investigated is the possible shadowing and/or focusing effect the Moon may have had on Earthbound objects. If the flux duration was long compared with the orbital period of the Moon 4 billion years ago, the effect is probably small unless the Moon was very close to the Earth.

EFFECTS OF BASIN-FORMING IMPACTS

The impact of a large object produces two immediate effects: the excavation and ejection of large amounts of crustal material, and the fracturing and brecciation of crustal rocks to great depths. The former is the more obvious, but the latter affects a greater volume of rock. Baldwin's (1963) data suggest a 500 km basin will have a depth of ~ 9.5 km. This is based on extrapolation of smaller craters and observed diameter-depth ratios, and therefore represents the minimum depth of the original crater. For example, Pike (1967) would argue for much greater depths for these basins; this only serves to enhance the effects discussed below. Basin depth modification results from back-falling ejecta, slumping and mass-wasting of the walls, isostatic adjustment of the basin topography, and possible filling by mare-type liquids.

Fragmentation of the underlying rock is severe. Data from Table XII of Baldwin (1963) and from Innes (1961) suggest a relation between the depth to the bottom of the brecciated layer (B) and the crater diameter (D):

$$\log B = 1.0232 \log D - 0.5905$$

which is a least squares fit to the above data. This is shown in Figure 4. The inset gives the results for terrestrial craters where drill cores have provided direct measurements. The curve is then extrapolated into the diameter range for basins. The two orders of magnitude extrapolation is probably not valid, but is at present the only available information.
A 500 km basin impact excavates almost 10 km of crust, but fractures rock to depths of $\sim$ 150 km.

To understand the effects of such an impact, a model of the crust and mantle for the Earth 4 billion years ago is needed. We adopt the following (Frey and Lowman, 1976): The crust is andesite with a bulk density of 2.7 gm/cm^3. The crust-mantle boundary is 20 km deep, which is consistent with Condie's (1973) suggestion that the Archaean crust thickened to 25-30 km between 3.5 and 3.0 billion years ago. The mantle is solid peridotite with a density of 3.3 gm/cm^3. These relations are shown in Figure 5. Geothermal gradients were probably higher in the past. We adopt 20°K/km, compared with the present day value (shown dashed) of roughly 10°K/km. The pressure melting curves for basalt (the partial melt product) and peridotite are also shown. The latter intersects the thermal gradient curve at roughly 70 km; below this the mantle is molten in this simple model.

Basin impacts initially produce a dichotomy in elevation. Two subsequent effects are expected: isostatic adjustment of the basin topography (which would tend to smooth out the elevation differences) and basaltic flooding of the basin (which would produce a compositional dichotomy between the basin floor and the highland crust). The thinner crust and higher thermal gradient of the Earth 4 billion years ago (compared to the Moon) suggest that isostatic adjustment of the basins should have been faster on this planet. As shown below, filling of the basins on the Earth was also rapid compared to the Moon, where major basins remained "dry" on the frontside for some 10^8 years and were never filled by mare basalts on the lunar farside.

Below the basin the pressure-temperature relations are changed in the sense that melting is favored at shallower depths. That is, the pressure drop due to large impacts causes the melting of "pressure frozen" material closer to the original surface, and therefore significantly closer to the new (deeper) surface level of the basin floor. For a basin 1000 km across, melting now occurs some 15 km closer to the new surface. Partial melting of the mantle in these regions produces a basaltic liquid with a density of $\lesssim 3.0$ gm/cm^3, which is overlain by solid but highly fragmented peridotite of density 3.3 gm/cm^3. The liquid would clearly rise in this situation and, being hotter than its surroundings, would encourage further melting as it rises. Near the surface hydrostatic pressure expands the liquid into the crater, flooding the basin with lava whose composition is quite different from that of the highlands. The rise time for the lavas should be $\sim 10^2$ years, based on seismic studies of Hawaiian basaltic eruptions. This rapid,

impact-triggered basin flooding is quite distinct from the late erupting mare basalts of the Moon, and results from the relatively thin lithosphere and high thermal gradient of the Earth. These combine to locate a magma source at depths which are shallow compared to the effects of brecciation due to impact. On the Moon, thermal conditions 4 billion years ago were such that rapid flooding could not have occurred, the mare basalts having been derived from relatively deep regions by partial melting (see Taylor, 1975) some 10^8 years after the basin formed. Backside basins have no appreciable mare fill, presumeably a consequence of greater crustal thickness overlying the source regions. For example, if lunar basalts were derived from depths >200 km, these liquids would lie below the region of intense fragmentation for all but the largest basins. Therefore, even _if_ a source of magma was available at the time of basin formation, penetration of this magman to the surface would have been significantly longer than in the case of the Earth, where brecciation reached well into the molten regions. Arkani-Hamed(1974) has shown that the lunar lithosphere beneath the basin thickens rapidly after basin formation, which would further hinder the rise of magma. This sub-basin thickening occurs on the Earth as well (Frey, 1977), but the shallow fragmented lithosphere of the early Earth presents little obstacle to rapid flooding following impact.

Remnants of these early post-basin volcanics may have been preserved in the ancient greenstone belts. Glickson(1976) suggests that some very old ultrabasic rocks are the products of temporally unique conditions on the early Earth, such as might be produced by very large impacts. Green(1972) called parts of the greenstone belts "terrestrial maria" and showed how

rapid pressure drops could produce the observed ultrabasic volcanics (Green, 1975). Because the rocks show no shock metamorphic effects, they must postdate the impact events (Glickson, 1976) as suggested above. We suggest that, like their lunar counterparts, these "mare basalts" were derived from the upper mantle by partial melting but, unlike the lunar case, penetrated the thin lithosphere of the Earth and erupted onto the basin floor in a very short time following the impact.

Because the thinning of the lithosphere is due principally to the impact, the situation described above probably represents a "worst case" for the Earth in that the depth-diameter relation used(Baldwin, 1963) is conservative and represents a minimum depth for these basins. Pike(1967) would argue for much deeper excavation; according to his calculations a 1000 km wide basin could have had an original depth of some 75 km, which means the impact would have punched completely through the lithosphere of 4 billion years ago and exposed a nearly molten, high density magma. The crustal compositional dichotomy would have been established immediately; isostatic adjustment would result in a basin floor of basic, 3.0-3.3 gm/cm^3 material some 3-4 km below the 2.7 gm/cm^3 intermediate highland crust. This adjustment should occur in some 10^3 years(Frey, 1977), which is slow compared even to the "worst case" basin flooding discussed above. While it is not clear that Pike's relations are any more applicable than Baldwin's formulas to the case of very large basins (where basin diameter greatly exceeds lithospheric thickness), it is clear that deeper excavation on the early Earth will serve to produce the crustal dichotomy more rapidly. More conservative depths for giant impact basins have basin filling on the

Earth delayed some 10^2-10^3 years, a time still significantly shorter than the filling of the lunar basins.

DISCUSSION

It would seem that, 4 billion years ago, the Earth experienced not only a period of intense bombardment but a subsequent period of extensive volcanic eruptions. The results described above indicate that the basin-forming period was quantitatively adequate to produce a crustal dichotomy comparable to the modern one from an original global crust. The Earth's first ocean basins were mare-type basins, and the original "oceanic" crust was mare-type fill in these basins. The modern oceanic crust, which is a product of plate tectonic processes, is a much reworked descendent of the original lowlands of the Earth formed by basin impacts.

Once established, the crustal dichotomy made possible the onset of plate tectonics. At first, a period of vertical tectonics was the major influence. Crustal uplift and rifting were probably initiated in the thinned crust of the Earth's mare basins(Frey, 1977). Loading of these basin margins by sediments encouraged subduction, which initially was probably confined to the continent/ocean(highland/mare)interface. With subduction established, sea floor spreading at mid-mare ridges could begin the long processes of(oceanic) crustal reworking, which, after several cycles, would eventually generate the young oceanic crust of the modern(post-Pangaea)plate-tectonics period. The remnant highlands were carried about, the pieces being first assembled into super-continents,then rifted apart as new oceans were born. For the last 2-3 billion years, horizontal tectonics have dominated the crustal development of the Earth.

The highland crust is not inactive during this period. Basin formation, basin flooding, rifting and spreading all compete with a gradual thickening of the continental or highland crust. Intrusive magmatism (Glickson, 1976), production of anomalous sialic "nuclei" such as in the Fiji Islands (Glickson, 1972) and lateral accretion play minor roles throughout the history of the Earth in the generation of new continental areas. Continental collisions and subsequent compression as well as minor underthrusting may account for minor losses in the areal extent of continents. These processes are hardly significant, however, compared to the establishment of the original curstal dichotomy.

If external events are responsible for the generation of this fundamental division of the Earth's surface, the implications are far reaching. We mention two examples below.

Without the production lowlying, higher crustal density areas it is unlikely that modern (horizontal) plate tectonics could have occurred. An intact global continental crust more than 5 km thick cannot be subducted (McKensie, 1969). Crustal uplift and rifting would produce a number of plates with nowhere to go. New material added at juvenile spreading centers could spread to nowhere, once minor compression had taken up the "jostling" of continental plates. Without subduction there would be no spreading. Vertical tectonics would dominate the scene. Crustal thickening would likely proceed more slowly in the early history of the Earth, but would eventually lead to very thick blocks pushed up by internal motions, only to slide back down. Volcanics would dominate orogeny, and Himalayan-like folds would not occur.

A somewhat more distressing implication is that for the evolution of life. Without ocean basins we picture a highland crust with many small patches of water which probably alternately dry and reform. It is questionable whether life could arise by means of chemical evolution without the stability of relatively permanent, deep, saltwater oceans. At the very best, evolution of such life forms could well differ significantly from that of the Earth. There would likewise be a severe change in the weather patterns if the heat sinks provided by the oceans were absent. If indeed the ocean basins are products of a flux of asteroids stored for 500 million years in the outer solar system (Wetherill, 1975), we must question the generality of such oceans on worlds near other stars. The implications for the development of extraterrestrial life are important, and will be examined elsewhere.

CONCLUSIONS

The two-fold crustal dichotomy of the Earth, which must have been present prior to the onset of global plate tectonics, can be derived from an original global crust through bombardment by basin-forming, Apollo type asteroids 4 billion years ago. The proximity of the Earth and Moon at this time requires that the Earth experience the same flux of objects responsible for the lunar mare basins. Scaling from the observed minimum number of lunar basins to the larger (gravitational) cross-section of the Earth and for the greater size of impact craters on the Earth indicates well over 50% of the Earth's surface was modified by basin-forming impacts.

The depth of the basins following isostatic adjustment and the rapid flooding of the lowlands by basaltic lavas established a combined topographic and compositional division of the crust, superficially resembling the modern dichotomy. Plate tectonic processes have since reworked principally the oceanic (mare) crust several times over, rearranging the configuration of the continental crust in the process.

If the oceans basins of the Earth ultimately have their origin in a period of impact bombardment of the inner solar system by a group of objects "stored" for half a billion years in the outer solar system, we must question the generality of oceanic materials and oceans themselves on planets in other star systems. Global crusts are probably common on terrestrial planets; deep, spreading ocean basins may be rare.

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FIGURE CAPTIONS

FIGURE 1. Impact parameters as a function of approach velocity. (a) Impact velocity at the surface of the Earth ($V_{\oplus}$) and the Moon ($V_{☾}$) and the ratio of these. (b) Ratio of basin diameters on the Earth to those on the Moon (for objects of identical mass) for two different values of k. (c) Gravitational radius compared to the physical radius for the Earth ($(R_g/R)_{\oplus}$) and for the Moon ($(R_g/R)_{☾}$), and ratio of the Earth's gravitational radius to that of the Moon.

FIGURE 2. (a) Histogram of basins as a function of diameter. Notation is the same as that used in column 1 of Table I. (b) Cumulative number versus diameter on a log-log plot for basins in Table I. Straight line is the highland crater distribution from Hartmann (1966). Inclusion of all basins from Table I suggests a distribution different from normal highland cratering.

FIGURE 3. (a) Total area affected by basins as a function of approach velocity for the Earth. Two cases are included: a minimum number of large, non-overlapping basins, and all basins and craters from Table I. (b) Percentage of Earth's surface disrupted by basin-forming impacts. For low velocities, the curves exceed 100% because there has been no correction for overlap.

FIGURE 4. Depth reached by excavation (depth of crater) and by fragmentation (depth of breccia) as a function of basin diameter. Crater depth is based on Baldwin's (1963) formulas. Depth to bottom of breccia is an extrapolation of the least squares fit shown as the inset, which is based on terrestrial crater data as reported in Baldwin (1963) and Innes (1961). The extrapolation is shown as the dotted line.

FIGURE 5. A pressure-temperature model for the Earth 4 billion years ago, as suggested by Frey and Lowman (1976a). The crust is andesite and 20 km thick. The mantle is solid peridotite down to ∿ 105 km. The adiabatic pressure-melting curves for peridotite (P) and basalt (B) are shown. Several geothermal gradients are also plotted.

FIGURE 6. Mare-type flooding of a large impact basin will be rapid on the Earth. Formation of the basin changes the pressure-temperature relations below the basin, and favors melting at shallower depths. The resulting liquid basalt is less dense (∿3 gm/cm^3) than the overlying fractured rock (3.3 gm/cm^3). The rise time is short compared to the isostatic adjustment of the basin topography (see text).

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TABLE I.

	BASIN		LONG	LAT	MOON DIAM (km)	MOON AREA ($10^5 km^2$)	MOON %	EARTH (V=17.5km/sec) DIAM (km)	EARTH AREA ($10^5 km^2$)	EARTH %	TOTAL AREA ($10^6 km^2$)	%	REMARKS
1	Imbrium	HW-B	19	+38	1340.0	14.100	03.7	1481.3	17.230	00.3	32.100	06.3	
2	W Nubium	HW-B	22	-24	425.0	1.419	00.4	469.8	1,734	00.0	3.229	00.6	inside C
3	Humorum	HW-B	39	-24	410.0	1.320	00.3	453.2	1.613	00.0	3.005	00.6	
4	Near Schiller	HW-B	45	-56	350.0	.962	00.3	386.9	1.176	00.0	2.190	00.4	
5	Bailly	HW-B	68	-67	300.0	.707	00.2	331.6	.864	00.0	1.609	00.3	
6	Grimaldi	HW-B	69	- 5	220.0	.380	00.1	243.2	.465	00.0	.865	00.2	
7	Pingre	HW-B	78	-56	300.0	.707	00.2	331.6	.864	00.0	1.609	00.3	
8	SE Limb	HW-B	94	-49	480.0	1.810	00.5	530.6	2.211	00.0	4.119	00.8	
9	Orientale	HW-B	95	-21	620.0	3.019	00.8	685.4	3.689	00.1	6.872	01.3	
10	Lorentz	HW-B	97	+34	330.0	.855	00.2	364.8	1.045	00.0	1,947	00.4	
11	Unnamed B	HW-B	123	+42	410.0	1.320	00.3	453.2	1.613	00.0	3.005	00.6	
12	Hertzsprung	HW-B	129	+ 1	285.0	.638	00.2	315.1	.780	00.0	1.452	00.3	
13	Birkhoff	HW-B	147	+59	320.0	.804	00.2	353.7	.983	00.0	1.831	00.4	
14	Apollo	HW-B	153	-36	435.0	1.486	00.4	480.9	1.816	00.0	3.383	00.7	inside G
15	Korolev	HW-B	157	- 4	405.0	1.288	00.3	447.7	1.574	00.0	2.932	00.6	
16	Unnamed D	HW-B	167	+18	600.0	2.827	00.7	663.3	3.455	00.1	6.435	01.3	
17	Antoniadi	HW-B	172	-69	140.0	.154	00.0	154.8	.188	00.0	.350	00.1	inside G
18	Ingenii	HW-B	197	-35	320.0	.804	00.2	353.7	.983	00.0	1.831	00.4	inside G
19	Poincare	HW-B	199	-58	335.0	.881	00.2	370.3	1.077	00.0	2.006	00.4	inside G

20	Moscoviense	HW-B	213	+26	410.0	1.320	00.3	453.2	1.613	00.0	3.005	00.6	
21	Mendeleev	HW-B	219	+ 6	330.0	.855	00.2	364.8	1.045	00.0	1.947	00.4	
22	Planck	HW-B	225	-58	325.0	.830	00.2	359.3	1.014	00.0	1.888	00.4	inside G
23	Schrodinger	HW-B	228	-75	320.0	.804	00.2	353.7	.983	00.0	1.831	00.4	inside G
24	Unnamed VI	HW-B	236	-81	335.0	.881	00.2	370.3	1.077	00.0	2.006	00.4	inside G
25	Milne	HW-B	247	-31	240.0	.452	00.1	265.3	.553	00.0	1.030	00.2	
26	Unnamed A	HW-B	252	-68	285.0	.638	00.2	315.1	.780	00.0	1.452	00.3	inside G
27	Compton	HW-B	256	+56	175.0	.241	00.1	193.5	.294	00.0	.548	00.1	
28	Smythii	HW-B	273	- 1	450.0	1.590	00.4	497.5	1.944	00.0	3.620	00.7	
29	Humboldtanium	HW-B	278	+58	600.0	2.827	00.7	663.3	3.455	00.1	6.435	01.3	
30	Crisium	HW-B	301	+16	450.0	1.590	00.4	497.5	1.944	00.0	3.620	00.7	
31	Fecunditatis	HW-B	312	- 3	520.0	2.124	00.6	574.8	2.595	00.1	4.834	00.9	
32	Janssen	HW-B	321	-43	160.0	.201	00.1	176.9	.246	00.0	.458	00.1	
33	Nectaris	HW-B	326	-15	840.0	5.542	01.5	928.6	6.772	00.1	12.610	02.5	
34	SW Tranquility	HW-B	337	+ 5	35[illegible]	.962	00.3	386.9	1.176	00.0	2.190	00.4	inside M
35	Serenitatis	HW-B	342	+25	680.0	3.632	01.0	751.7	4.438	00.1	8.266	01.1	
A	Sinus Aestuum	SA-B	10	+15	[illegible]0.0*	.491	00.1	276.4	.600	00.0	1.117	00.2	inside B
B	"Fauth"	SA-B	20	+15	1200.0*	11.310	03.0	1326.5	13.820	00.3	25.740	05.0	overlaps 1
C	Nubium	SA-B	20	-20	750.0	4.418	01.2	829.1	5.399	00.1	10.060	02.0	
D	S Procellarum	SA-B	50	-10	710.0*	3.959	01.0	784.9	4.838	00.1	9.011	01.8	
E	Question - [illegible]	SA-B	120	+55	?	?	?	?	?	?	?	?	No basin?

F	"Anderson"	SA-B	190	+20	600.0*	2.827	00.7	663.3	3.455	00.1	6.435	01.3	Not 16 ??
G	"Super Basin"	SA-B	190	-53	2100.0*	34.640	09.1	2321.5	42.330	00.8	78.830	15.4	
H	Cyrano"	SA-B	200	-10	480.0*	1.810	00.5	530.6	2.211	00.0	4.119	00.8	
I	Schwarzschild	SA-B	240	+70	205.0	.330	00.1	226.6	.403	00.0	.751	00.1	
J	Question - 2	SA-B	250	0	?	?	?	?	?	?	?	?	No basin?
K	Mare Marginis	SA-B	265	+20	475.0*	1.772	00.5	525.1	2.166	00.0	4.033	00.8	
L	Mare Australe	SA-B	275	-45	900.0(?)	6.362	01.7	994.9	7.774	00.2	14.480	02.8	Rim unclear
M	Tranquility	SA-B	300	+10	750.0*	4.418	01.2	829.1	5.399	00.1	10.060	02.0	
N	Question - 3	SA-B	350	-20	?	?	?	?	?	?	?	?	No basin?
O	Mare Vaporum	SA-B	355	+15	250.0*	.491	00.1	276.4	.600	00.0	1.117	00.2	
I.	Procellarum	IMAB	58	+18	900.0*	6.362	01.7	994.9	7.774	00.2	14.480	02.8	
II.	N Procellarum	IMAB	63	+40	450.0*	1.590	00.4	497.5	1.944	00.0	3.620	00.7	
III.	"Euclides"	IMAB	28	- 8	450.0*	1.590	00.4	497.5	1.944	00.0	3.620	00.7	
a	Boltzman	HW-C	115	-55	200.0	.314	00.1	221.1	.384	00.0	.715	00.1	
b	Landau	HW-C	119	+42	220.0	.380	00.1	243.2	.465	00.0	.865	00.2	
c	Zeemann	HW-C	134	-75	201.0	.317	00.1	222.2	.388	00.0	.722	00.1	
d	Mach	HW-C	149	+18	205.0	.330	00.1	226.6	.403	00.0	.751	00.1	
e	Gabis	HW-C	152	-14	205.0	.330	00.1	226.6	.403	00.0	.751	00.1	
f	Oppenheimer	HW-C	166	-36	215.0	.363	00.1	237.7	.444	00.0	.826	00.2	
g	Leibnitz	HW-C	182	-38	250.0	.491	00.1	276.4	.600	00.0	1.117	00.2	
h	Von Karmann	HW-C	184	-48	240.0	.452	00.1	265.3	.553	00.0	1.030	00.2	

i	D'Alembert	HW-C	196	+52	220.0	.380	00.1	243.2	.465	00.0	.865	00.2	
j	Campbell	HW-C	209	+45	235.0	.434	00.1	259.8	.530	00.0	.987	00.2	
k	Gagarin	HW-C	211	-20	270.0	.573	00.2	298.5	.700	00.0	1.303	00.3	
l	Fermi	HW-C	237	-19	240.0	.452	00.1	265.3	.553	00.0	1.030	00.2	T
m	Pasteur	HW-C	255	-12	235.0	.434	00.1	259.8	.530	00.0	.987	00.2	
aa	Clavius	LC	15	-58	230.0m	.416	00.1	254.3	.508	00.0	.946	00.2	
bb	Sinus Iridium	LC	30	+43	300.0m	.707	00.2	331.6	.864	00.0	1.609	00.3	inside 1
cc	Schickard	LC	55	-43	210.0m	.346	00.1	232.1	.423	00.0	.788	00.2	
dd	Hausen	LC	89	-65	140.0m	.154	00.0	154.8	.188	00.0	.350	00.1	
ee	Mendel	LC	110	-50	155.0m	.189	00.0	171.3	.231	00.0	.430	00.1	
ff	Rowland	LC	162	+57	170.0m	.227	00.1	187.9	.277	00.0	.517	00.1	
gg	Fabry	LC	251	+42	170.0m	.277	00.1	187.9	.277	00.0	.517	00.1	
hh	Belkovich	LC	272	+62	210.0m	.346	00.1	232.1	.423	00.0	.788	00.2	

NOTES:

% = Percentage of surface area

HW-I = Basin diameters from Hartmann & Wood

HW-C = Crater diameters from Hartmann & Wood

SA-B = Basin diameters from Stuart-Alexander & Howard

IMAB = Irregular Maria-Artificial Basin diameter measured by author from Figure 14 of Howard et al.

* = Basin diameters measured by author from Figure 14 of Howard et al.

m = Large crater diameters measured by author

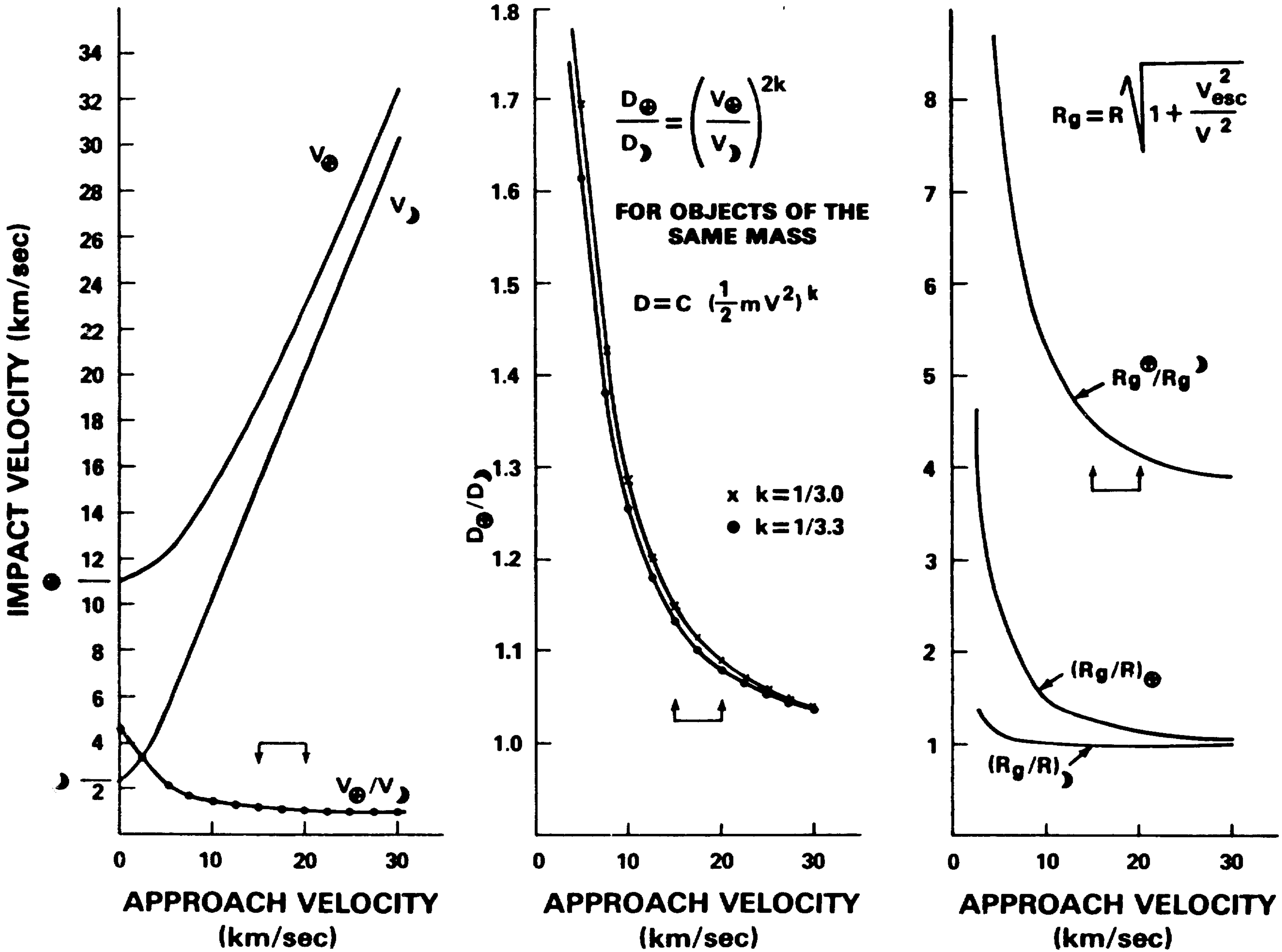
Question - 1, 2, 3: Basins from Stuart-Alexander & Howard, but rim not obvious

T : Fermi + Tsiolkovsky have combined diameter of 340 km

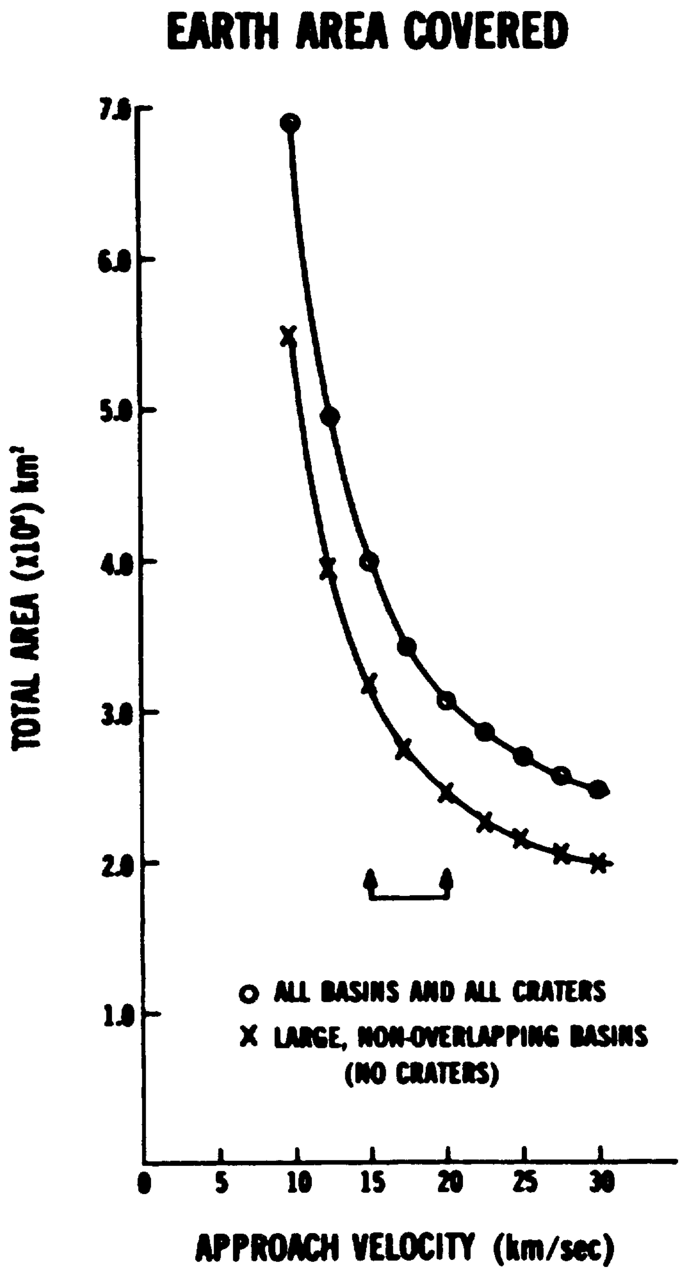
Mare Australe : Diameter from Stuart-Alexander & Howard, but rim not obvious

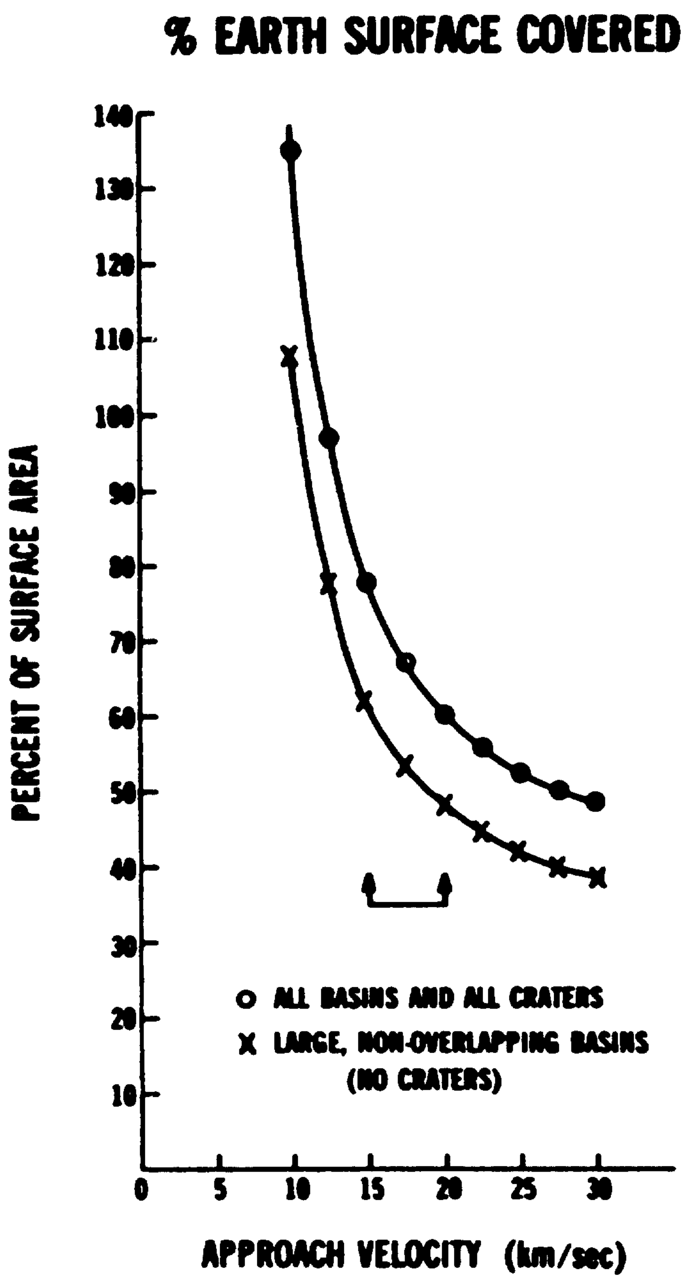
* * * * * * *

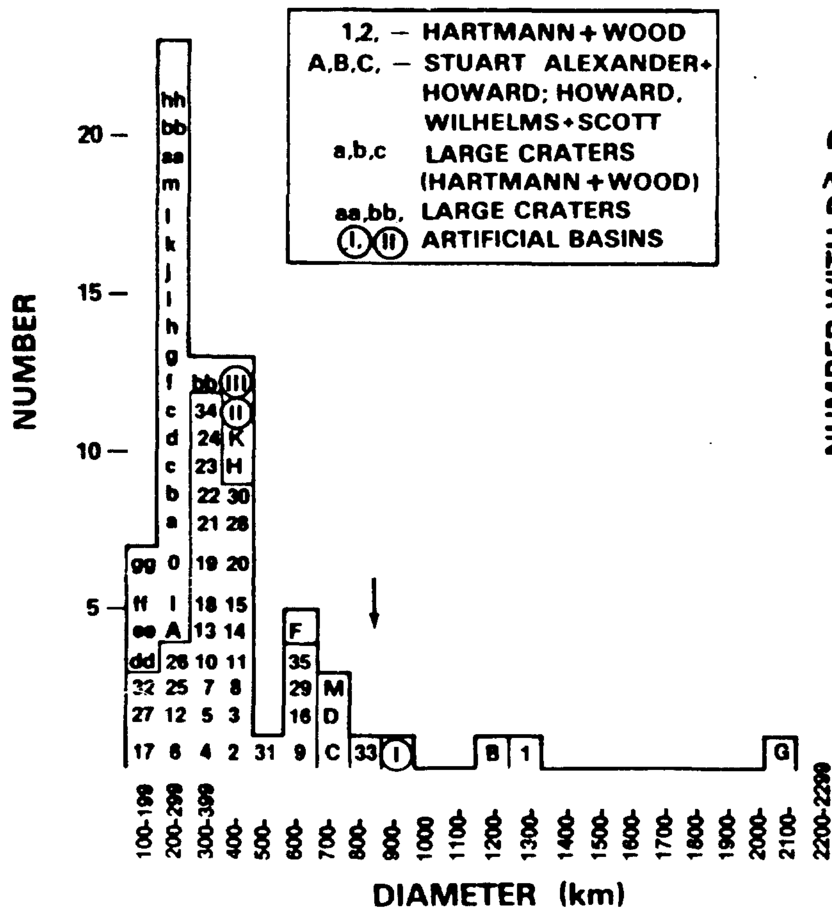
Total area of Moon covered:	150.200×10^5 km^2	or	0.396	All basins and all craters
Total basin area on Earth:	341.870×10^6 km^2	or	0.669	(V_a = 17.5 km/sec)
Total area of Moon covered:	119.740×10^5 km^2	or	0.315	Large, non-overlapping basins only
Total basin area on Earth:	272.530×10^6 km^2	or	0.533	(V_a = 17.5 km/sec)



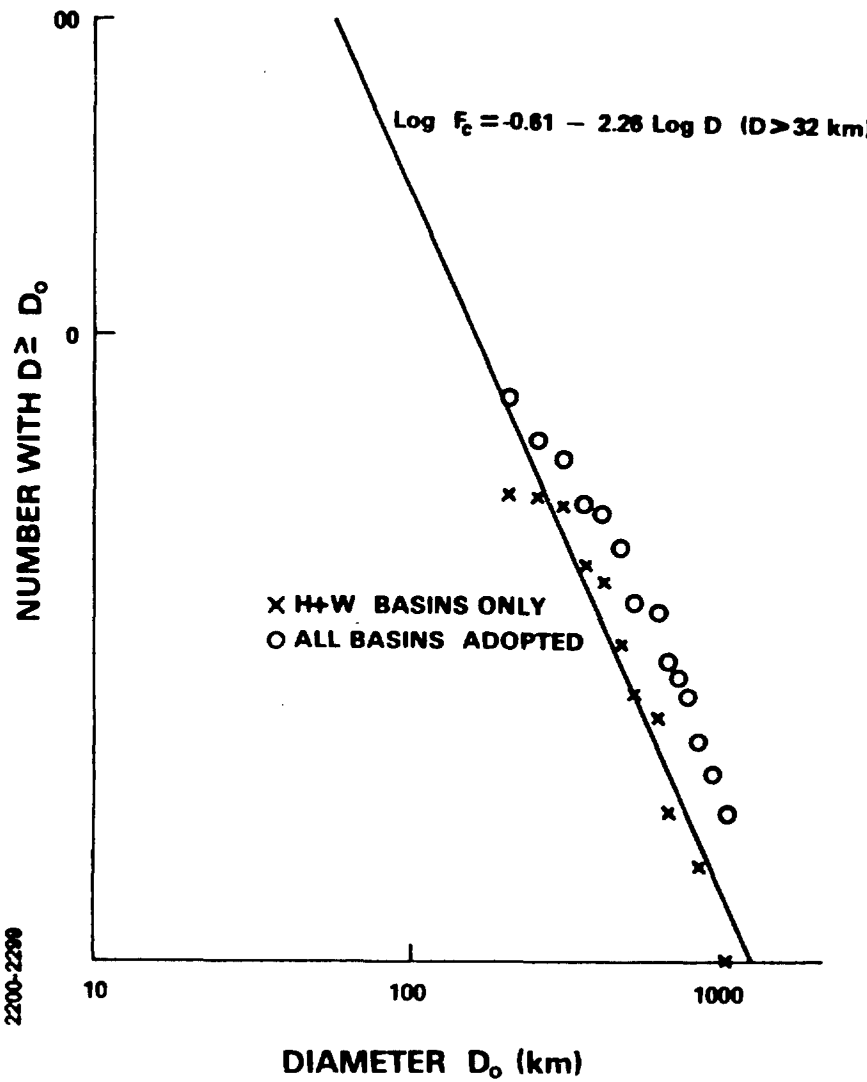
IMPACT VELOCITY (km/sec)
$V_\oplus$
$V_☾$
$V_\oplus/V_☾$
APPROACH VELOCITY (km/sec)
$D_\oplus/D_☾$
$\frac{D_\oplus}{D_☾} = \left(\frac{V_\oplus}{V_☾}\right)^{2k}$
FOR OBJECTS OF THE SAME MASS
$D = C\ (\frac{1}{2} m V^2)^k$
x k=1/3.0
● k=1/3.3
APPROACH VELOCITY (km/sec)
$R_g = R\sqrt{1 + \frac{V_{esc}^2}{V^2}}$
$Rg^\oplus/Rg^☾$
$(R_g/R)_\oplus$
$(R_g/R)_☾$
APPROACH VELOCITY (km/sec)


EARTH AREA COVERED
TOTAL AREA (x10⁸) km²
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
5
10
15
20
25
30
APPROACH VELOCITY (km/sec)
O ALL BASINS AND ALL CRATERS
X LARGE, NON-OVERLAPPING BASINS (NO CRATERS)

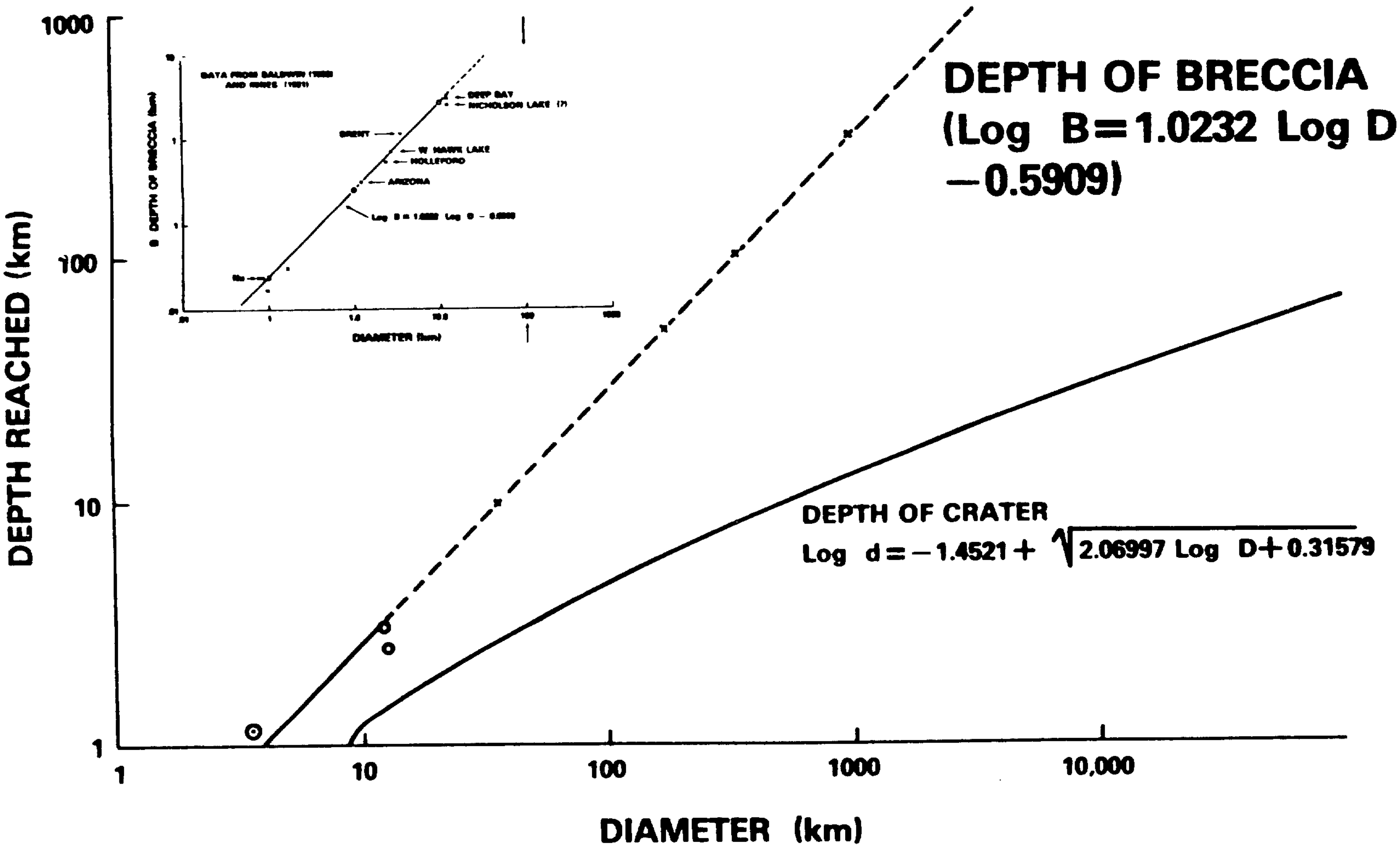

% EARTH SURFACE COVERED
PERCENT OF SURFACE AREA
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
APPROACH VELOCITY (km/sec)
O ALL BASINS AND ALL CRATERS
X LARGE, NON-OVERLAPPING BASINS (NO CRATERS)

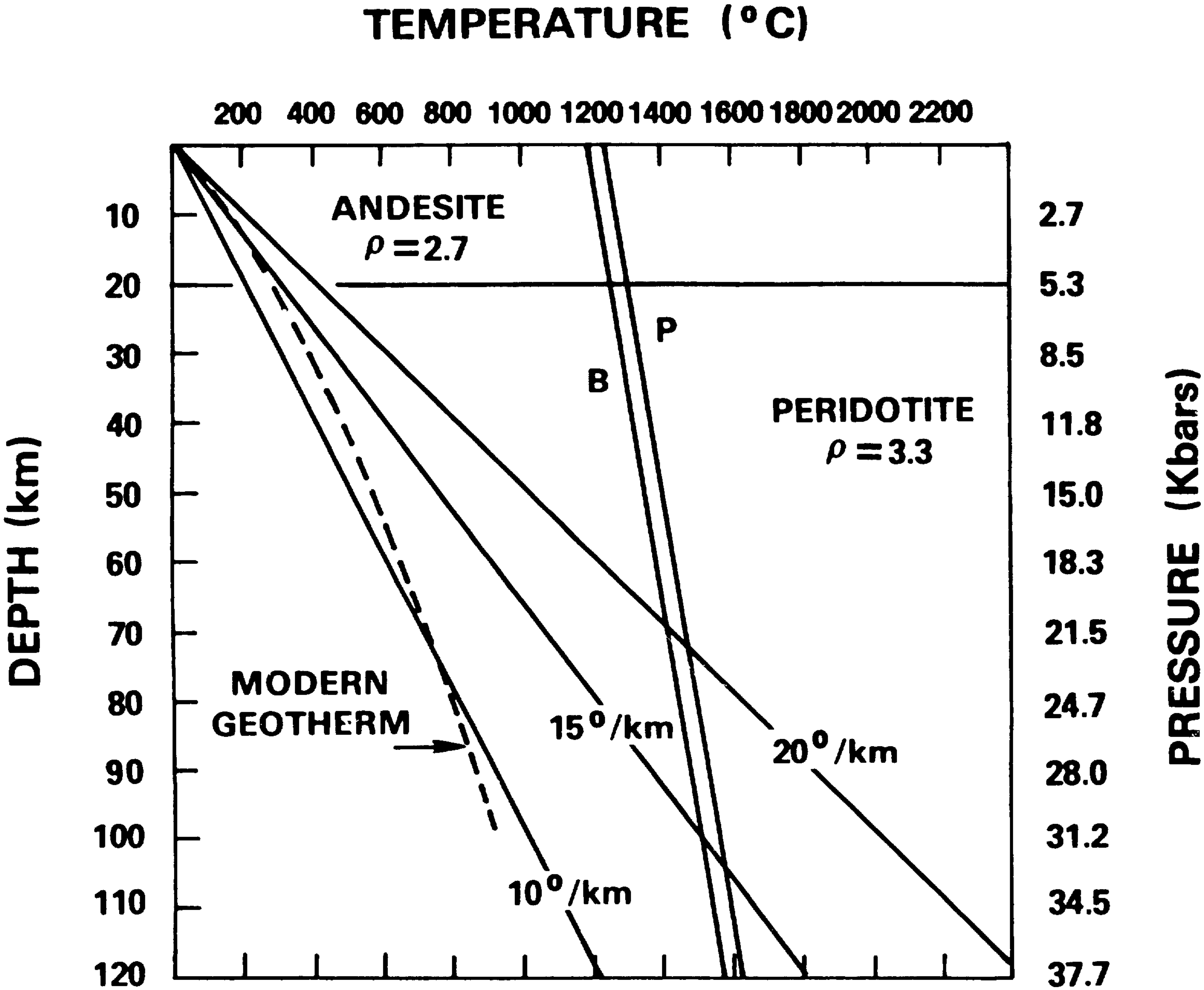


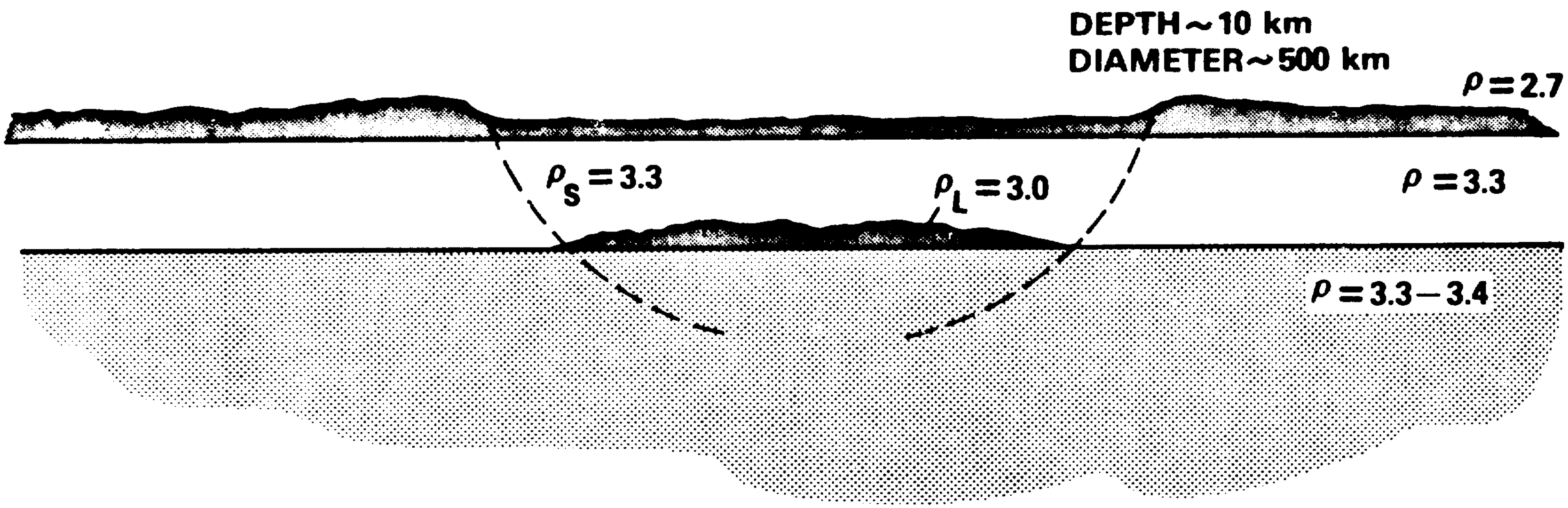
1,2, — HARTMANN + WOOD
A,B,C, — STUART ALEXANDER + HOWARD; HOWARD, WILHELMS + SCOTT
a,b,c LARGE CRATERS (HARTMANN + WOOD)
aa,bb, LARGE CRATERS
I, II ARTIFICIAL BASINS
NUMBER
DIAMETER (km)



Log F_c = -0.61 — 2.26 Log D (D > 32 km)
NUMBER WITH D ≥ D_o
× H+W BASINS ONLY
○ ALL BASINS ADOPTED
10
100
1000
DIAMETER D_o (km)


DEPTH OF BRECCIA
(Log B=1.0232 Log D
−0.5909)
DEPTH OF CRATER
Log d=−1.4521+√2.06997 Log D+0.31579
DEPTH REACHED (km)
DIAMETER (km)
1000
100
10
1
1
10
100
1000
10,000
DEEP BAY
NICHOLSON LAKE (?)
BRENT
W. HAWK LAKE
HOLLEFORD
ARIZONA
DEPTH OF BRECCIA
DIAMETER


TEMPERATURE (°C)
200 400 600 800 1000 1200 1400 1600 1800 2000 2200
ANDESITE
ρ = 2.7
P
B
PERIDOTITE
ρ = 3.3
MODERN
GEOTHERM
15°/km
20°/km
10°/km
DEPTH (km)
10 20 30 40 50 60 70 80 90 100 110 120
PRESSURE (Kbars)
2.7 5.3 8.5 11.8 15.0 18.3 21.5 24.7 28.0 31.2 34.5 37.7


DEPTH ~ 10 km
DIAMETER ~ 500 km
ρ = 2.7
ρS = 3.3
ρL = 3.0
ρ = 3.3
ρ = 3.3 – 3.4